

Enhanced Spectral Efficiency Using Bandwidth Switchable SAW Filtering for Mobile Satellite Communications Systems

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ABSTRACT

Currently proposed mobile satellite communications systems require a high degree of flexibility in assignment of spectral capacity to different geographic locations. Conventionally this results in poor spectral efficiency which may be overcome by the use of bandwidth switchable filtering.

Surface acoustic wave (SAW) technology makes it possible to provide banks of filters whose responses may be contiguously combined to form variable bandwidth filters with constant amplitude and phase responses across the entire band. The high selectivity possible with SAW filters, combined with the variable bandwidth capability, makes it possible to achieve spectral efficiencies over the allocated bandwidths of greater than 90%, while retaining full system flexibility. Bandwidth switchable SAW filtering (BSSF) achieves these gains with a negligible increase in hardware complexity.

INTRODUCTION

Mobile satellite communications systems must operate with very limited bandwidth allocations and must serve a wide variety of inexpensive terminals. For a given transmitter power, the EIRP and figure of merit (G/T) are enhanced by dividing the spectrum between a number of spot beams, each serving a different geographical region. For maximum operational efficiency, flexibility is needed in the allocation of bandwidth to different beams; this generally requires a large number of filters, with a corresponding loss in spectral efficiency due to the guardbands between adjacent channels. The conflict between flexibility and spectral utilisation can be removed by the use

of contiguous filter banks, where adjacent filters may be operated simultaneously to provide a single continuous channel.

The second section of this paper describes the various filtering options, and shows the advantages of bandwidth switchable filtering using contiguous filter banks. The third section considers surface acoustic wave (SAW) transversal filters, describing both currently achievable performance and basic performance tradeoffs, and shows that they are the most suitable components for this application. The fourth section discusses the design of bandwidth switchable SAW filter banks, and the fifth section describes experimental data obtained at COM DEV on a trial three-channel filter bank at 150 MHz.

BANDWIDTH SWITCHABLE FILTERING

Figure 1 shows the general transponder configuration while Figure 2 shows the corresponding frequency channelisation. Bandwidth switchable filtering is a technique for replacing adjacent filters in a particular beam by a single filter covering the same total bandwidth; as illustrated in Figure 3, this avoids wasting the guardband regions between individual filters. If a continuous band of frequencies is always assigned to a particular beam, then the filters within that band may be replaced by a single equivalent filter. With this scheme, guardbands are only required between beams and not between individual filters, and spectral efficiency is greatly increased.

The simplest method of implementing a bandwidth switchable filter system would be to provide separate equivalent filters for every combination of adjacent channels that might be employed. However, for any reasonably flexible system, this would involve a large increase in system cost and complexity, not to

mention the extraordinarily difficult shape factors that would be required for the broadband filters. As discussed later in the paper, SAW technology offers a solution to this problem. SAW filter banks may be designed such that adjacent filters operated in parallel act as a single continuous filter. This provides all the advantages of bandwidth switchable filtering, while retaining essentially the same transponder configuration as that illustrated in Figure 1.

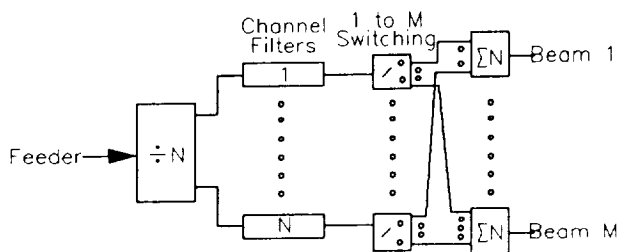


Figure 1. Flexible Transponder Configuration

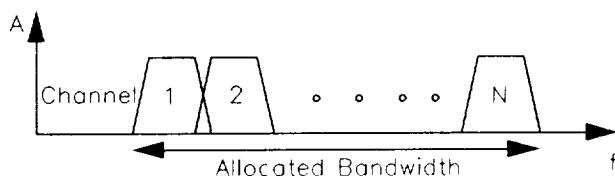


Figure 2. Spectral Channelising

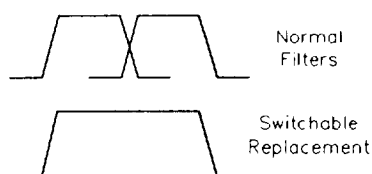


Figure 3. Switchable Filters

Spectral efficiency is defined as the ratio of the usable bandwidth to the allocated channel bandwidth [1]. For mobile communications systems, the available bandwidth (WARC 87) is small. This puts a premium on the efficient utilisation of the bandwidth due to its sensitivity in determining the revenue earning capability of satellites. In addition, spectral efficiency is also of importance on the satellite feed links

where there are also bandwidth restrictions. This is of particular importance where the L-band spectrum is reused.

Mobile satellite communication systems also require flexible assignment of communications capacity between beams. Conventional filtering systems can only achieve this at the expense of spectral efficiency or at increased cost and complexity in the satellite.

One method of subdividing the L-band spectrum is by the use of filters which overlap at their passband edge as shown in Figure 4. By assigning adjacent filters to non-overlapping beams, no L-band spectrum is lost. This approach has a number of deficiencies. The constraint of adjacent filter assignment to non-overlapping beams severely restricts the flexibility of the system while the translation to the feeder band, as shown in Figure 4, also restricts the designer in employing bandwidth switchable filtering. It restricts each beam to employing a maximum of 50% of the spectrum separated into non-adjacent channels. Also, the feeder allocation requires at least two times the L-band bandwidth for each frequency use, unless individual local oscillators are used for the filters, which is prohibitively inefficient and costly. Additional problems are also encountered due to the overlapping regions of the filters.

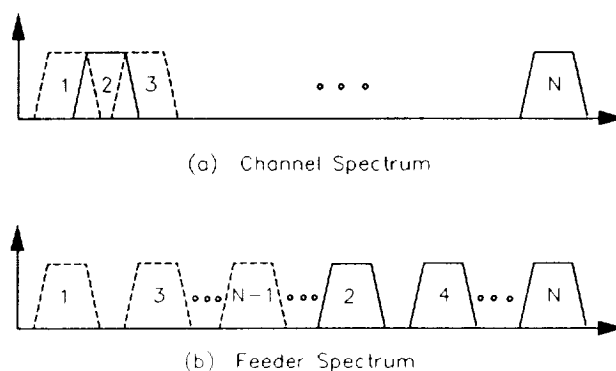


Figure 4. Overlapping Spectrum Channelisation

Non-Overlapping Filters

The preferred method of subdividing the L-band spectrum is by the use of filters which do not overlap within the passband, as shown in Figure 2. This approach allows any beam to access any number of channels up to the full L-band capacity and is not restricted in flexibility. Also, the feeder allocation only requires the L-band bandwidth for each frequency use. However this approach cannot achieve 100% spectral efficiency. The minimum passband separation required is dictated by the filter transition width. The spectral efficiency is thus directly related to the filter characteristics and the number of filters by the following equations:

$$B = (B_T - (N-1)B_t)/N \quad (1)$$

$$E = 100 N B / B_T = 200 / (1 + S); N > 1 \quad (2)$$

B_T total bandwidth available
 N number of channels across band
 B_t filter transition bandwidth
 B bandwidth for each channel
 S filter shape factor = $1 + 2B_t/B$
 E effective system L-band spectral efficiency (%)

Bandwidth Switchable Filtering

The bandwidth switchable filtering approach uses non-overlapping filters as shown in Figure 2 but can also connect filters which cover any combination of channels. By only assigning adjacent filters to individual beams, the spectral efficiency becomes dependent only on the number of beams simultaneously sharing the L-band spectrum, the level of frequency reuse and the number of unswitched divisions of the band. These divisions occur where the L-band spectrum is divided into a number of independent sub-bands, each of which is supported by a bandwidth switchable filter bank. The maximum spectral efficiency and usage is given in these cases by the following equations:

$$U = 100(1 - (D-1)B_t/B_T) \quad (3)$$

$$E = 100(1 - ((DM/R) - 1)B_t/B_T) \quad (4)$$

M number of beams in the system

D number of sub-bands
 U maximum L-band spectral usage per beam (%)
 R frequency reuse factor
 E effective system L-band spectral efficiency (%), when all M beams are active in each sub-band.

Comparison of Filtering Options

Table 1 shows a relative comparison of the options discussed above. The system assumed uses the WARC forward L-band allocation of 29 MHz, excluding the 1 MHz search and rescue (SAR) band; it has 9 beams and reuses the L-band spectrum 3 times. To achieve system flexibility the spectrum is subdivided into 4 separate sub-bands, each of which is further divided by 8 filters, each with transition bandwidths of 200 kHz.

For mobile satellite communications, where capacity assignment flexibility is a key requirement, bandwidth switchable filtering offers the optimum performance in all respects and achieves very high spectral efficiency.

Table 1 : Comparison of Filter Options

Parameter	Over-lapping	Non-Over-lapping	Switched
L-band spectral efficiency (%)	100	77.9	92.1
Maximum L-band spectrum available per beam (%)	50	77.9	97.9
Capacity assignment flexibility	Poor	Good	Good
Feeder spectral efficiency (%)	50	77.9	92.1

SURFACE ACOUSTIC WAVE FILTERS

Proposed mobile satellite systems typically require filters with amplitude and phase ripples of 0.8 dB and 5° p-p respectively, transition bands of 200 kHz, channel bandwidths from a few hundred kilohertz to a few megahertz, and rejections of 40 dB close-in and 50 dB further out. The bandwidth and shape factor specifications limit the IF frequency to the VHF region, and the only possible technologies are miniature LC filters, crystal filters, or SAW transversal filters. Low inductor Q makes LC technology unsuitable for highly selective filters, and crystal resonators cannot accommodate the required range of bandwidths. SAW filters, however, can meet the proposed specifications, and they have the additional virtues of small size, low weight, and linear phase response; furthermore, they have a very simple structure which makes them highly reliable.

The basic structure of a SAW bandpass filter is shown in Figure 5. It consists of a polished substrate of some piezoelectric material with an aluminum electrode pattern formed photolithographically on the surface. The electrodes form two separate transducers, each consisting of a pair of busbars with numerous parallel electrodes running between them. The surface acoustic wave propagates in a direction parallel to the busbars and perpendicular to the electrodes. The principle of operation is almost identical to that of a finite impulse response (FIR) digital filter. Each transducer acts as a tapped delay line with each electrode functioning as an individual tap; the weighting function is implemented by moving the positions of the electrode breaks in the region between the busbars. The weighting function is closely related to the impulse response, which is $\sin x/x$ for a bandpass filter, and this can be clearly seen by examining the break pattern in a SAW transducer.

For classical filters the complexity is usually determined by the required number of poles. This concept is not applicable to SAW filters, and a more appropriate measure is the required impulse response duration. If a bandpass filter has a passband ripple of $20 \log \left(\frac{1+\delta_p}{1-\delta_p} \right)$ dB and a stopband level of $20 \log \delta_s$, then it is known semi-empirically that:

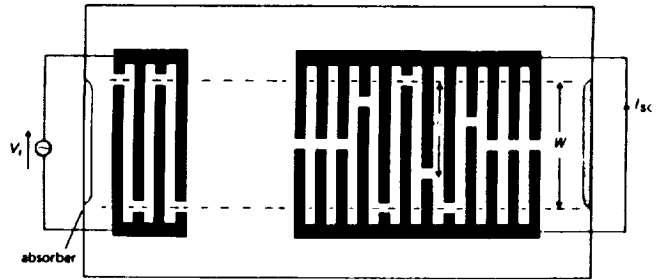


Figure 5. Simplified SAW Bandpass Filter Structure

$$\log (\delta_p \delta_s) \approx -1.05 - 1.45 B_f T, \quad (5)$$

where B is the transition bandwidth and T is the required length of impulse response [2]. The impulse response duration is therefore independent of the absolute filter bandwidth, and for the proposed specification all filters would be of essentially the same size. Shape factor is not directly constrained by impulse response duration; however, low shape factors require $\sin x/x$ weighting functions with narrow mainlobes and numerous small sidelobes which are difficult to implement accurately.

SAW devices usually employ one of three materials, lithium niobate, lithium tantalate, or quartz. Lithium niobate exhibits the strongest piezoelectric effect, and is good for broad band devices, but it has a poor frequency/temperature coefficient (-75 to -94 ppm/ $^\circ\text{C}$ depending on orientation). At the other extreme, quartz is only weakly piezoelectric, but it can have a zero first-order temperature coefficient. The most popular quartz substrate, the ST-cut, has a frequency temperature law:

$$\frac{\Delta F}{F} = -3 \times 10^{-8} (T - T_0)^2. \quad (6)$$

T_0 is nominally 25°C , but can be varied by slight adjustments to the substrate orientation. Hence, a 100 MHz quartz filter with a 60°C operating range would move by only 2.7 kHz if T_0 were placed in the centre of the range. For satellite applications, size, weight, reliability and power consumption are at a premium, and quartz filters, which avoid the use of ovens, are the preferred choice.

Lithium niobate filters rarely have both transducers in line as in Figure 5; instead, they are linked by another component called a multistrip coupler; this has the advantage of allowing each transducer to be weighted without restriction. For quartz the transducers must be placed directly in line, and although unrestricted weighting, called apodisation, can be applied to one transducer, the electrode breaks in the other must be placed at the extremes of the aperture, adjacent to one busbar or the other; this restricted form of weighting is usually called withdrawal weighting. The performance achievable with quartz filters is reduced by these constraints, but it is still adequate for the purpose.

The following list of parameters represents proven performance limits for quartz. All limits can be achieved simultaneously and some can be exceeded at the expense of others.

Passband amplitude ripple, dB	< 0.5
Passband phase ripple, p-p	< 3°
Stopband rejection, dB	> 50
Centre frequency, MHz	< 200
Shape factor	> 1.2
Fractional bandwidth, %	< 5
Transition bandwidth, kHz	> 200

The fractional bandwidth limit is imposed by the low piezoelectric coupling of quartz; it is likely that the limits on passband ripple and shape factor will be improved in the future. It is advisable to restrict centre frequency to 200 MHz; this is not a firm limit, but filter performance does start to degrade beyond this point.

The insertion loss of SAW filters is usually fairly high, typically 20 - 30 dB. This is not due to acoustic attenuation, which is very small, but to the bi-directionality of the transducers and to the electrical mismatch with the source and load. The high mismatch makes the filter characteristics insensitive to variations in the source and load impedance, and reduces unwanted acoustic signals. There are techniques for making true low loss SAW filters, but these increase complexity and reduce filter performance. For the proposed satellite application, the simplest device structure operated with a 25 - 30 dB insertion loss appears to be the most appropriate choice.

The surface wave velocities for all commonly used materials are in the range 3000 - 4000 m/s; a microsecond of impulse response therefore translates into 3 - 4 mm of substrate length. Allowing for various margins, and for factors such as transducer spacing, the overall length of devices conforming to the proposed specification would be 6 - 7 cm.

BANDWIDTH SWITCHABLE SAW FILTERING

The concept of bandwidth switchable SAW filtering (BSSF) is quite simple [3]. In this implementation it consists of a bank of contiguous filters with overlapping transition regions. Each individual filter must satisfy the general channel specification, and when adjacent filters are operated in parallel the responses in the common transition region must add vectorially to produce a continuous, composite passband response.

For a quartz SAW filter most of the frequency selectivity is provided by one transducer, which is consequently much larger than the other. If the tap weights in this transducer are $\{h_n\}$, and the electrode time spacing is τ , then the frequency response can be written:

$$H(\omega) = A(\omega) \sum_n h_n e^{-j\omega n\tau},$$

where $A(\omega)$ includes the response of the second transducer. The design problem therefore involves the approximation of the desired response by a linear function of the tap weights. This problem may be solved by one of two standard methods, the most popular being the Remez exchange algorithm [4]; the alternative approach is to use linear programming, which offers unrivalled flexibility, but is computationally expensive. These optimal methods have now largely displaced window functions as a design tool.

With these methods it is easy to design filters with specified transition region characteristics. Fortunately, the transition response required for BSSF differs only slightly from the unconstrained form, and other parameters are little affected, although the filter is somewhat squarer than it would otherwise have been. Linear phase SAW filters are particularly easy

to design, and two such contiguous filters designed to cross at their 6 dB points are quite a good approximation to the BSSF requirement.

As will be seen in the next section, the key to success in designing individual filters and BSSF systems is in the modelling of second order effects, particularly diffraction and circuit loading. Current simulation techniques are very accurate, but the very high precision required for satellite channeliser applications shows that weaknesses still exist.

EXPERIMENTAL RESULTS

The results described in this section represent the initial data from the first BSSF designs attempted at COM DEV. To simplify the preliminary assessment, the BSSF filters were designed to operate in a 50 Ω system without matching circuits, and this accounts for the high insertion loss. In practice, matching circuits would be used and the effects of these would have to be allowed for in the design. However, the initial purpose was to assess the intrinsic properties of the SAW devices without extraneous complications.

The BSSF trial filter set consisted of three devices, each with design ripples of 0.3 dB and 2°p-p in the passband, and transition widths of 200 kHz. The centre frequencies were 147.8 MHz, 150 MHz, and 152.2 MHz. Practical BSSF systems would probably use filter bandwidths less than the value of 2 MHz chosen here; however, the purpose of this exercise was to define performance limits, and for this reason filters with a low shape factor of 1.2 were selected. Figure 6 shows the superimposed response of the three filters as measured directly on a network analyzer; no matching circuits were used; the amplitude levels were within 1 dB of prediction and so closely matched that no balancing was necessary. For greater clarity, Figures 7 and 8 show the experimental and theoretical responses respectively for the 150 MHz filter. The agreement is very close, except for the stopband region which is degraded by spurious acoustic signals. The stopband in Figure 6 is limited by electromagnetic breakthrough in the

device package, and this effect has been gated out in Figure 7 to give a clearer view of the acoustic response.

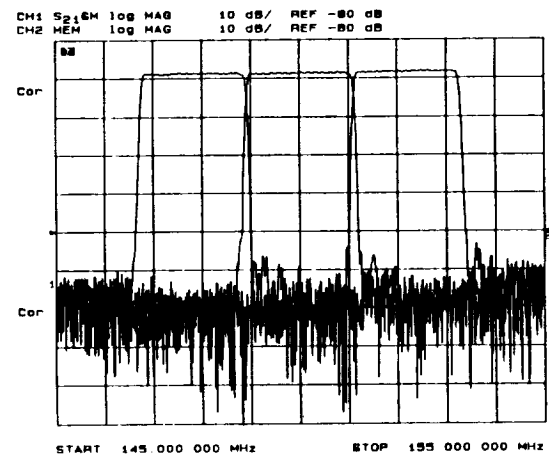


Figure 6. Superposed Filter Responses

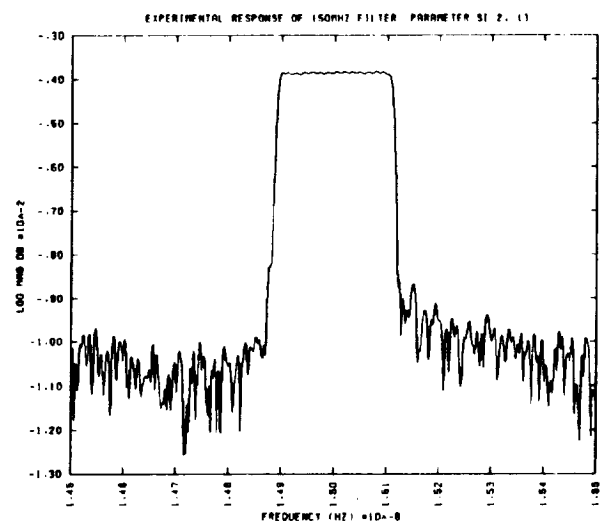


Figure 7. Gated Response of 150 MHz Filter

To assess the properties of the devices when interconnected in BSSF mode, the four S-parameters of each filter were accurately measured, and the various modes of interconnection were then simulated on the computer. This approach was used in the interests of speed and flexibility.

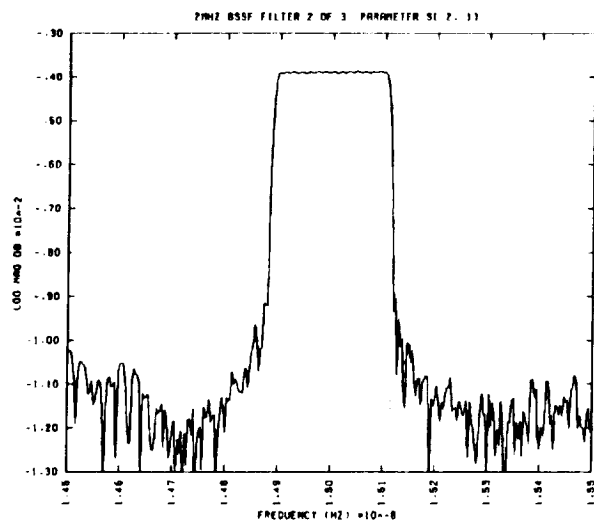


Figure 8. Theoretical Response of 150 MHz Filter

The first method of interconnection employed $50\ \Omega$ power dividers to couple the input and output ports. Figure 9 shows the composite response, again using gating to remove electromagnetic breakthrough; Figures 10 and 11 show detailed passband amplitude and phase responses without gating. The experimental filters showed absolute phase offsets of several tens of degrees, though this was as great within devices of the same type as between devices of different types. The responses in Figures 9, 10 and 11 therefore used phase shifters to balance the phase response, but no amplitude adjustment was employed. The degradation of amplitude ripple in the transition regions can be clearly seen, though the target specification of 0.8 dB is almost met. The excess amplitude ripple can be considerably reduced by adjusting the phase shifters, but this degrades the phase response.

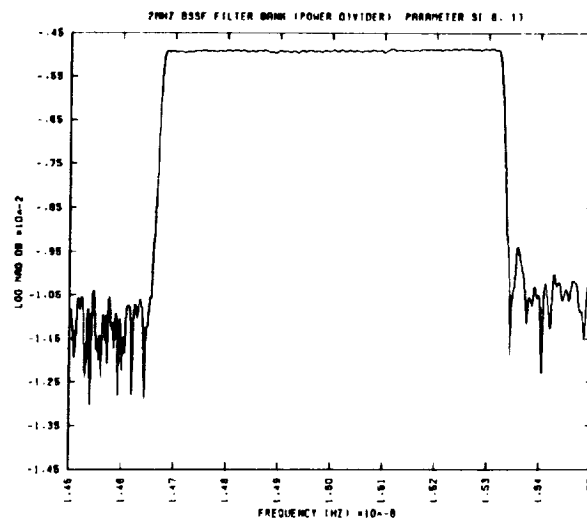


Figure 9. Combined Filter Amplitude Response Using Power Divider Coupling

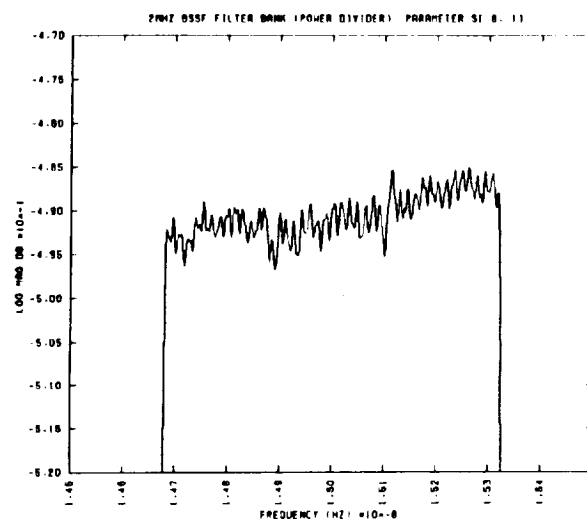


Figure 10. Combined Passband Amplitude Response Using Power Divider Coupling

The slight tilt on the filter passbands is in accord with the design, as they were intended to operate in BSSF mode with the inputs and outputs directly connected. The corresponding responses for this mode of interconnection are shown in Figures 12, 13, and 14. In this case, a small degree of amplitude correction (0.4 dB) was employed. However, the overall ripple was

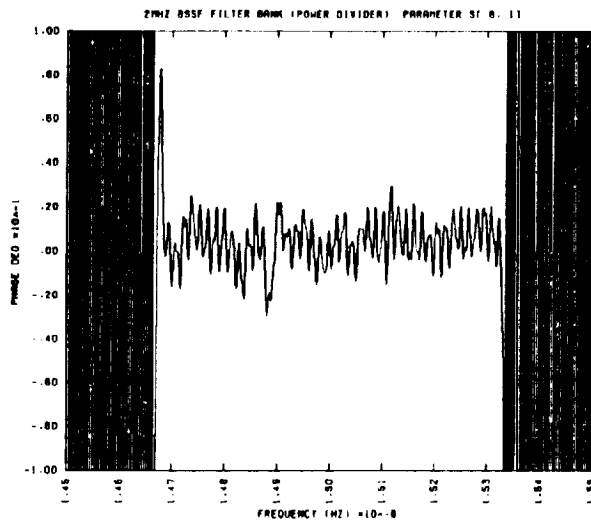


Figure 11. Combined Phase Response Using Power Divider Coupling

not greatly different from that in the power divider case. The use of direct coupling at either the input or the output ports has advantages in reducing component count in the final system, but it may produce difficulties due to reduced isolation.

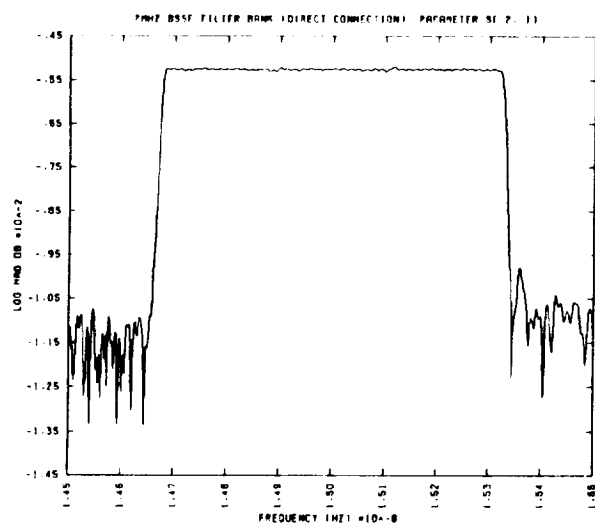


Figure 12. Combined Filter Amplitude Response Using Direct Coupling

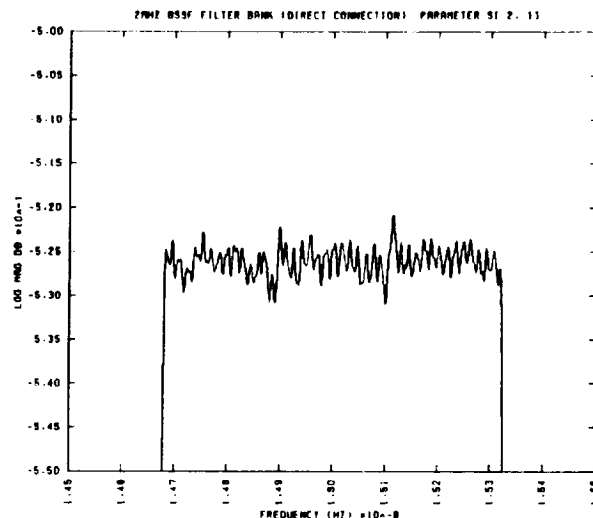


Figure 13. Combined Passband Amplitude Response Using Direct Coupling

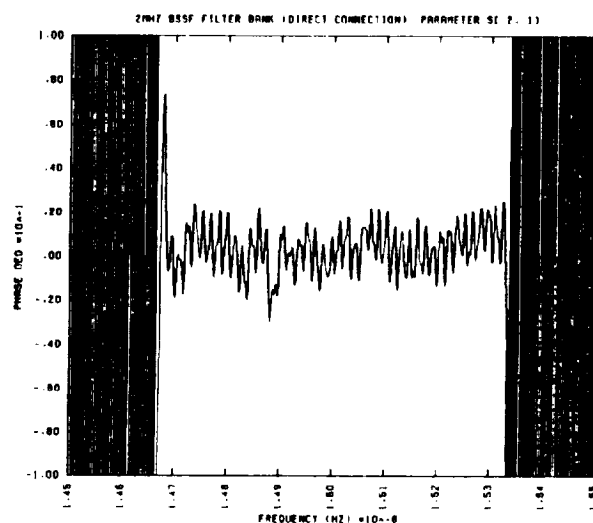


Figure 14. Combined Passband Phase Response Using Direct Coupling

These results show that the SAW devices are intrinsically very well balanced in amplitude. The absolute phase shift through the devices is over 6×10^5 degrees, and some phase imbalance between production filters is expected. However, it appears to be somewhat high at the moment, possibly due to strain in the substrate mounting. Some external adjustment of

amplitude and phase balance will always be necessary, and, in practice, this would be largely provided by the matching circuits. Use of external circuit elements would also permit optimisation of the transition region.

This initial assessment has firmly established the feasibility of the BSSF concept and its implementation using SAW filters.

The measured results are in close agreement with theory, and the specifications are almost satisfied. There is no doubt that BSSF performance can be further enhanced by fairly simple additions to existing SAW filter modelling programs.

CONCLUSIONS

It has been demonstrated that bandwidth switchable filter banks can provide flexibility in the allocation of available channel capacity without sacrificing spectral efficiency. SAW transversal filters are the only devices that can meet the proposed mobile satellite specifications; and they have the additional advantage that their natural shape is very close to that required for bandwidth switchable SAW filtering (BSSF).

The feasibility of BSSF has been tested with a set of three, high selectivity quartz filters chosen to test the limits of the technology. The agreement with theory is good, and the specifications are almost met. Measured data

indicates that simple refinements in device modelling and optimisation of matching circuits will permit significant enhancement of performance, allowing all specification requirements to be met or exceeded.

ACKNOWLEDGEMENT

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